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Polarization characteristics of ULF waves detected onboard GEOS-1. Problems encountered and practical solutions

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In this work we will show how we are able to study the principal characteristics of the Ultra Low Frequency (ULF) waves detected onboard the GEOS-1 spacecraft, and especially the time evolution of amplitude and polarization. First, we will show the main results of our studies, and then we will show the methods used in the data processing, the encountered problems and the practical solutions used to solve them.

Slide 1:

This figure represents an example of summary experimenter, which allows us to sum up in two frames of 3 hours the principal characteristics of the ULF waves detected above GEOS-1.

On frame one, at the top, we provide a time-frequency diagram that we call a spectrogram, which represent across a grey-level palette, the power spectral density (PSD) of the waves. We use three circular components, Left, Right and Z longitudinal components, by respect to the Z axis of the spacecraft, which is the rotation axis (spin axis).

The PSD is increasing when the grey level go to dark. The grey scale is logarithmic, and the total dynamic is 40 decibels. The correspondence between the grey levels and the physical value of the PSD is given in nT^2/Hz .

Other useful informations are given at the bottom, but we have to check the θ angle which is the angle between the spin axis and the Bo DC magnetic field. A low value (ideally close to zero) indicates a good validity of the signal separation into Left and Right components, and thus gives directly the polarization of the waves.

On frame two, at the bottom, we represent the time evolution of the power of the signal, integrated over various frequencies ranges, between 0 and 11.5 Hz, which is the Nyquist frequency.

We now explain the way in which they were realized, and the practical problems encountered and how we solve them.

Slide 2:

The analysis method used to process the signal is the one defined by Koderá et al, valid for plane waves. We use the two X and Y components perpendicular to the spin axis and we form the complex signal:

$$S_{xy}(t) = x(t) + i y(t)$$

This signal is decomposed by a FFT not in a base of sine functions, but in a base of circular functions, Left and Right. The negative frequencies of this FFT give directly the Left mode, that is to say the plane wave rotating in the left sense by respect to the spin axis, while the positive frequencies give the Right mode. This means also that a plane ellipsoid wave is decomposed in two circular waves, of opposite rotation sense. Thus, a single Fourier transform directly give the amplitude and polarization in each modes of the detected waves.

We can see on the top of this slide three examples of plane monochromatic waves and the Fourier transform of their associated S_{xy} complex signal.

On the bottom of this slide, we can see how the circular components are useful to pass from a spinning referential to a fixed one. As it is the case for GEOS-1, when the measurement frame is spinning around the rotation axis, at a spin frequency f_s included in the frequency range of the detected waves, the change of coordinate system usually done in the time domain reduce, with circular components, to a translation in frequency domain:

$$S_{xy}(f) = S_{xy}(f + f_s)$$

Where $S_{xy}(f)$ is the power spectral density in the spinning plane and $S_{xy}(f)$ the PSD in a fixed coordinate system. The schematic diagram at the bottom of this slide illustrates this relation: for example, the large static magnetic field B_0 is seen, by the rotating sensors, as a left circular wave of frequency $-f_s$. This ray is in fact strongly weakened, about 25 dB, by an onboard hardware despin system, to avoid telemetry saturation. Because in practice this hardware despin system is slightly different on x and y components, about 3 dB, the DC magnetic field B_0 is seen by the sensor not as a left-handed circular wave, but as an elliptic one. So we observe a second ray on the right mode, a $+f_s$ in spinning system.

After translation to pass into a fixed system, we get two spin rays, the first one and the most important at $f=0$, and the second one, more weak, at $f=2f_s$.

Because the transfer function $\alpha(f)$ of the search coil is equal to zero at $f=0$, we also notice than a right-hand wave at frequency $-f_s$ cannot be recorded by the experiment. After calibration, that is to say mainly a division of the spectrum by $\alpha(f)$, this frequency $f=0$ becomes undefined. After translation to get data in a fixed system, this is of course the frequency $+f_s$ which is undefined.

Slide 3:

On this slide we show the comparison between the X-Y-Z spectrum (top) and the R-L-Z spectrum (bottom). For the two cases, the data have been calibrated to obtain the DSP in nT²/Hz.

X-Y-Z spectra are in spinning system, R-L-Z spectra have been translated of f_s to get data in fixed system.

For X-Y-Z spectra, only the no-spinning Z component show a single event at ~0.52 Hz, while for X and Y the Doppler effect split the event in two part, one shifted by $-f_s$, the other by $+f_s$, according the respective part of left and right component in the XY plane. The left part is accelerated of f_s , while the right part is decelerated of f_s . A slight signal appears at the spin frequency on the Z component, due to the small misalignment between the Z sensor and the true spin axis (~1 degree).

On the other hand, in the case of R-L-Z spectra, the event is seen at the same frequency on the 3 components. As seen on the schematic diagram of the previous slide, an undefined frequency at f_s and a spin ray at $2f_s$ are present only on the Right mode, while the Left mode is perfectly clean.

So, by computing with such a method consecutive spectra, and by set to zero the parasite line at $2f_s$, we can obtain an improved version of the summaries, with a CPU time very low since the signal processing used is very simple.

Nevertheless, some disturbing effects still appear, as we can see on slide 4.

Slide 4:

The most important one is seen on this example (top): On many summaries, we can see a very strong modulation on the PSD, covering all the frequency range. It is amplified on the integrated power curves, and can present various forms from day to day.

We realized that this modulation is due to the fact than the Fourier transform was taken over a time which is not an integer multiply of the spin period, whereas the spin frequency is the major component of the signal (10 to 100 more high than waves). Since Fourier transform assume a periodical signal over the window used, a great and non significant discontinuity appears.

The shape of the modulation is very sensitive to the exact value of the spin frequency, which can change of about 3% during operations. A numerical simulation (bottom) has shown that this was the correct interpretation, and leads us to define a method to eliminate the large spin component in the signal. So we have set up a software despin system to completely remove the spin sine in the signal. This method require the exact value of the spin frequency, with an accuracy better than 1%, but this is not a problem since this value is available in the house keeping data of the spacecraft. Furthermore, the software is less consuming of CPU time, and gives the amplitude

and the phase of the spine sine. This is an important benefit, since these two values allow us to compute the two components of the DC field in the spin plane.

Slide 5:

On this slide we show the spectrum of the S_{xy} complex signal with and without the application of the despin software. We can see that the software is very efficient: The pick at $f=0$ (corresponding to the DC field) is deeply reduced while the pick at $2 f_s$ completely disappears. Furthermore, the software application has an effect on all the frequencies: the signal/noise ration has been increased, and the spectrum is improved.

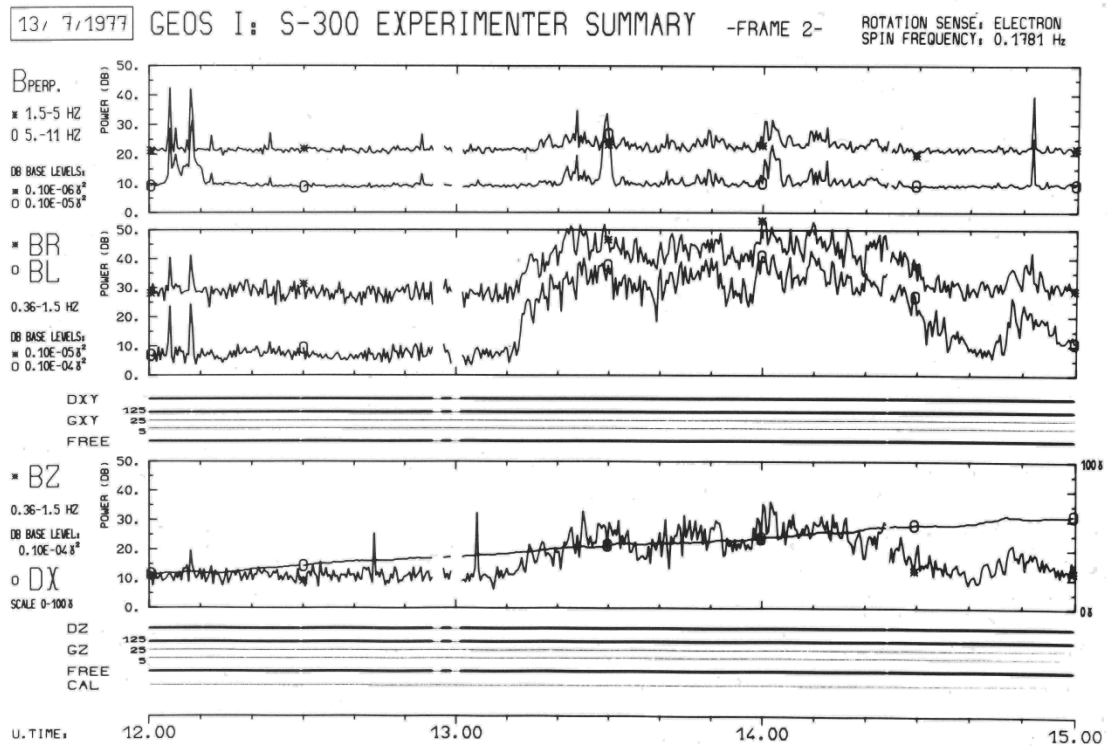
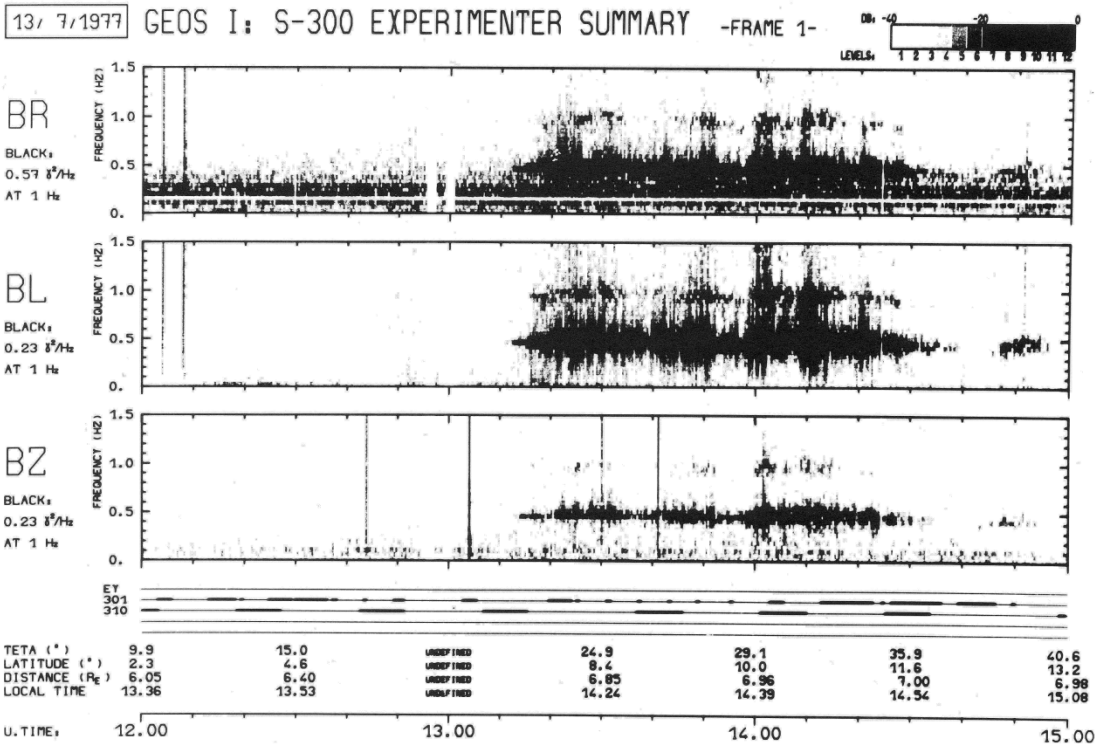
Slide 6:

On this slide we show the comparison between summaries computed before and after the application of the despin software system, during an event with a very strong perpendicular DC field, until hardware saturation (500 nT). The event becomes visible both on the spectrogram as on the integrated power curves, in the corresponding frequency range.

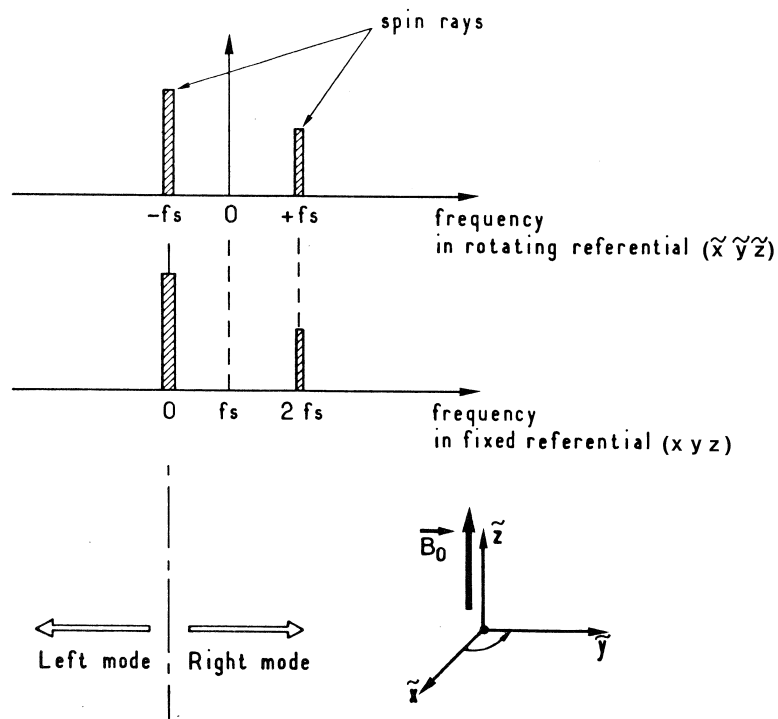
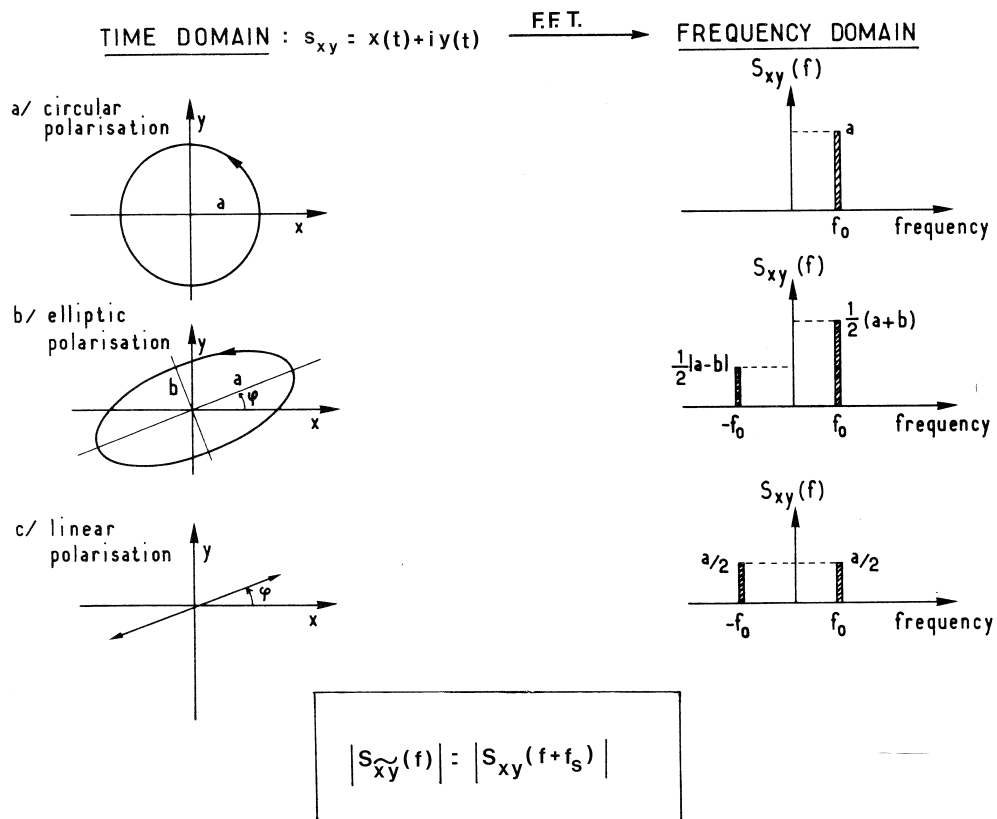
Slide 7:

This is an example of routine plots before and after application of the despin software system in normal conditions. Not only the modulation and the second harmonic of the spin frequency have disappeared, but a physical event becomes visible at ~ 0.4 Hz. This event becomes also visible on the integrated power curves, in the corresponding frequency range. Routine plots such as this example is now perfectly clean.

In conclusion, the application of this software is essential to get clean experimental summaries. It is fast in computing time, and associated with a complex FFT the production summaries covering all the time life of GEOS data is now possible.



Slide 1. Example of experimentateur summarie covering 3 hours data in two frames.

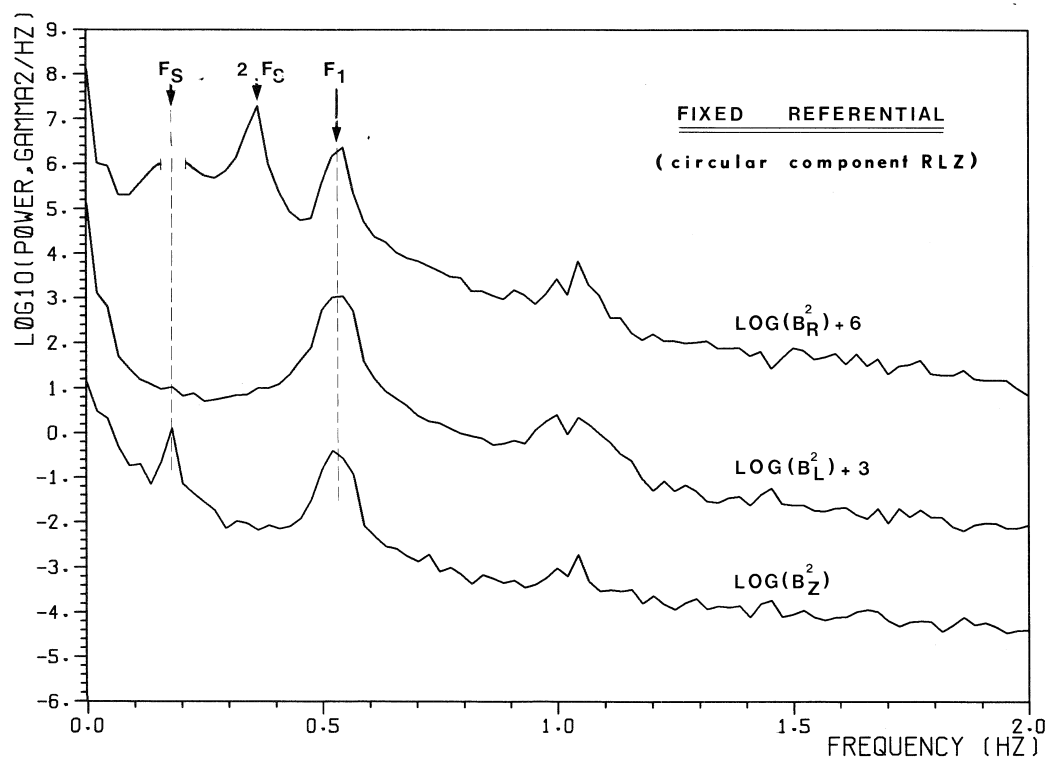
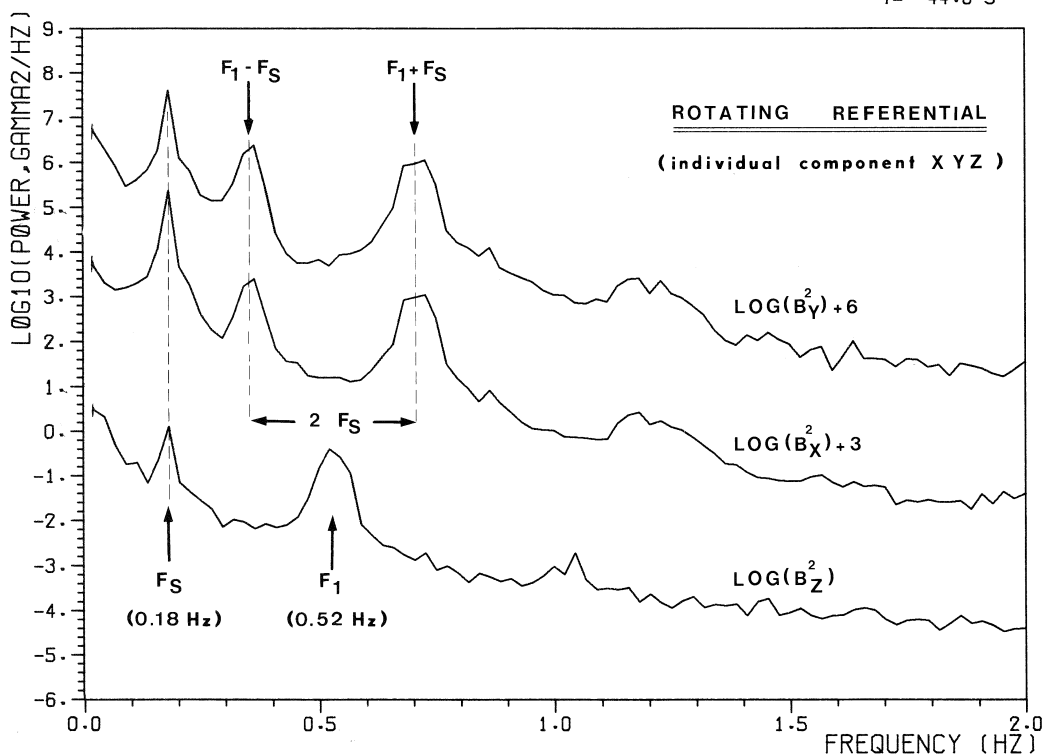


Slide 2. Top: Fourier transform associated to the S_{xy} complex signal, for 3 examples of monochromatic plane wave. Bottom: Correspondence between frequencies measured in the rotating system of reference of the sensors and in a fixed system.

GEOS-1 ULF SPECTRA

JULY 13, 1977 13H 24M 50S - 13H 30M 43S

DF=0.023 HZ
T= 44.0 S



Slide 3. Comparison between spectral analysis of Cartesian x-y-z components (top) and circular Sxy components (bottom)

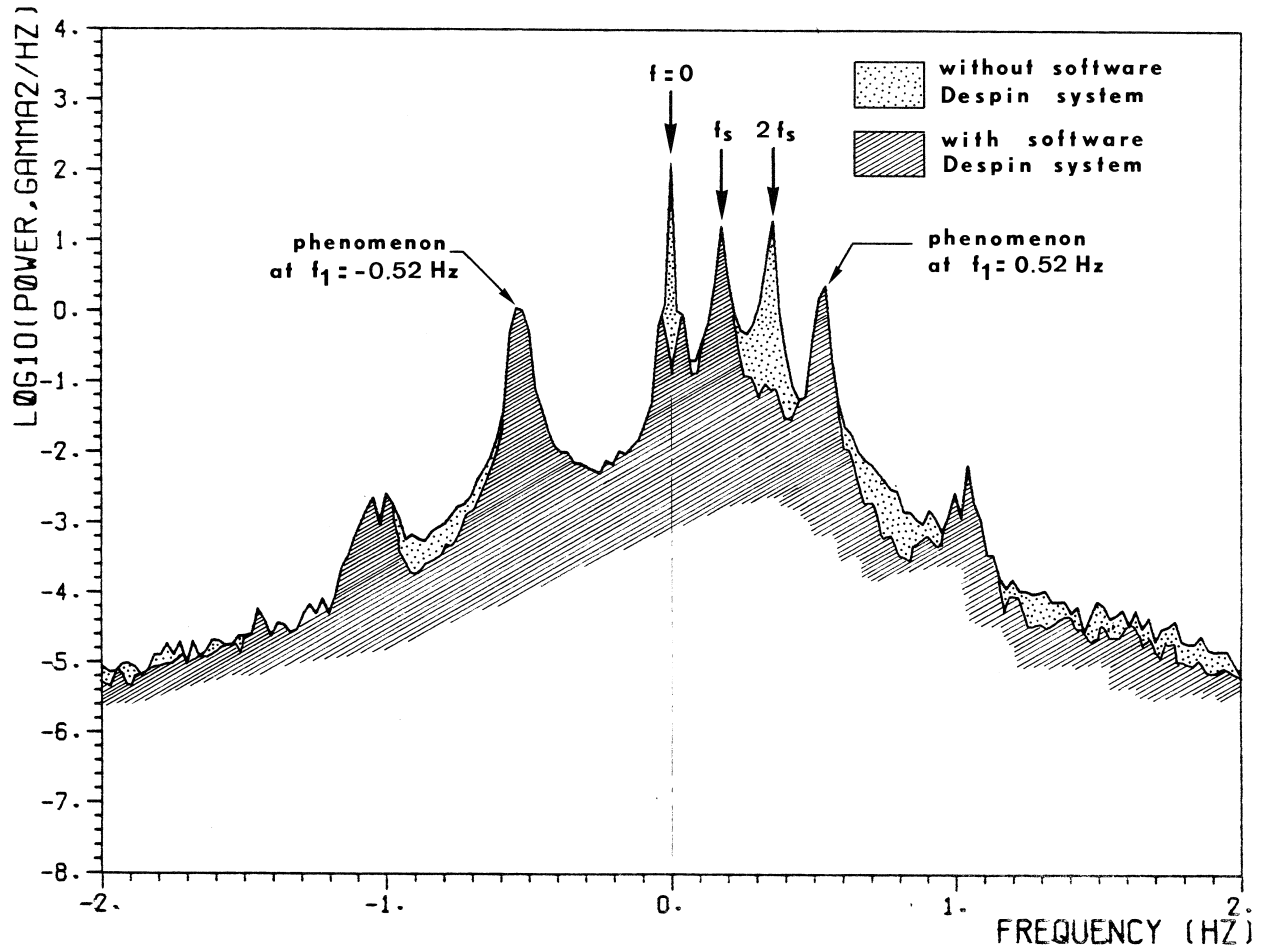


$\Delta f = 2\%$

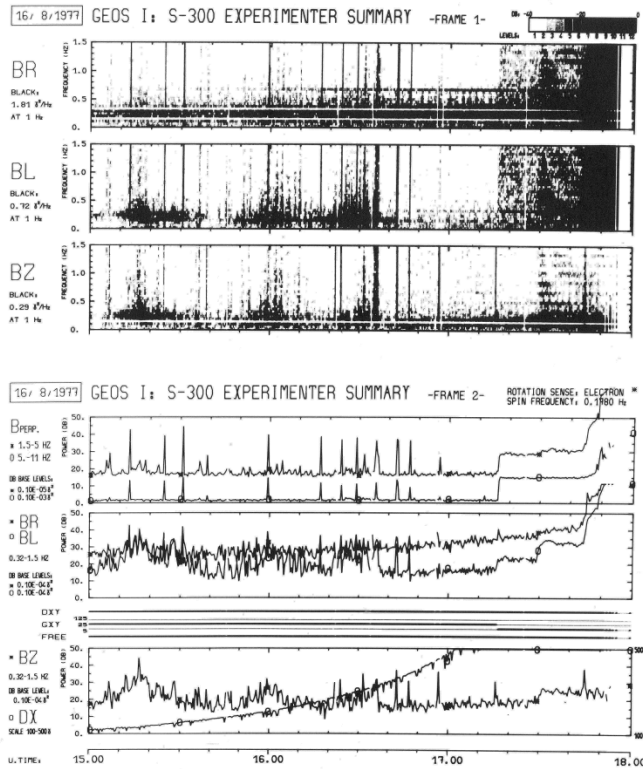
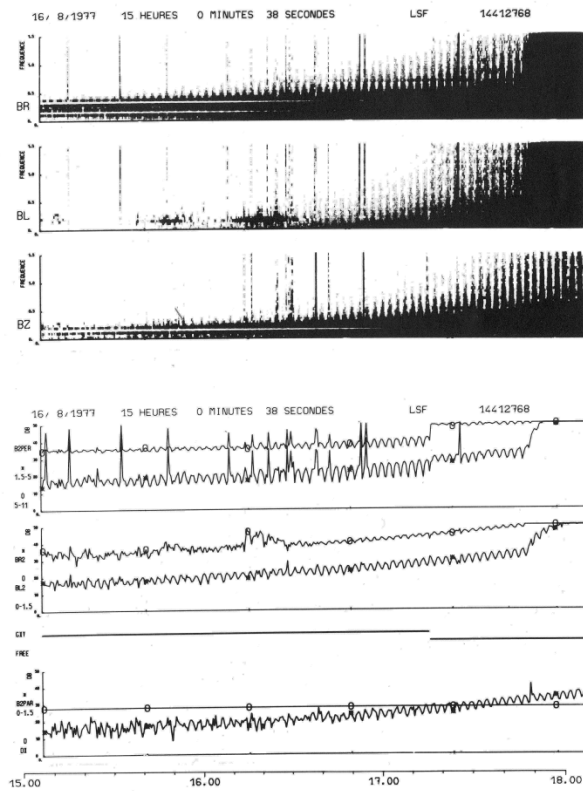
Slide 4. Example of power spectral density modulation during the time (consecutive spectra) due to the truncature of strong sine component in the signal.

GEOS-1 ULF SPECTRA

JULY 13, 1977 13H 24M 50S - 13H 30M 43S

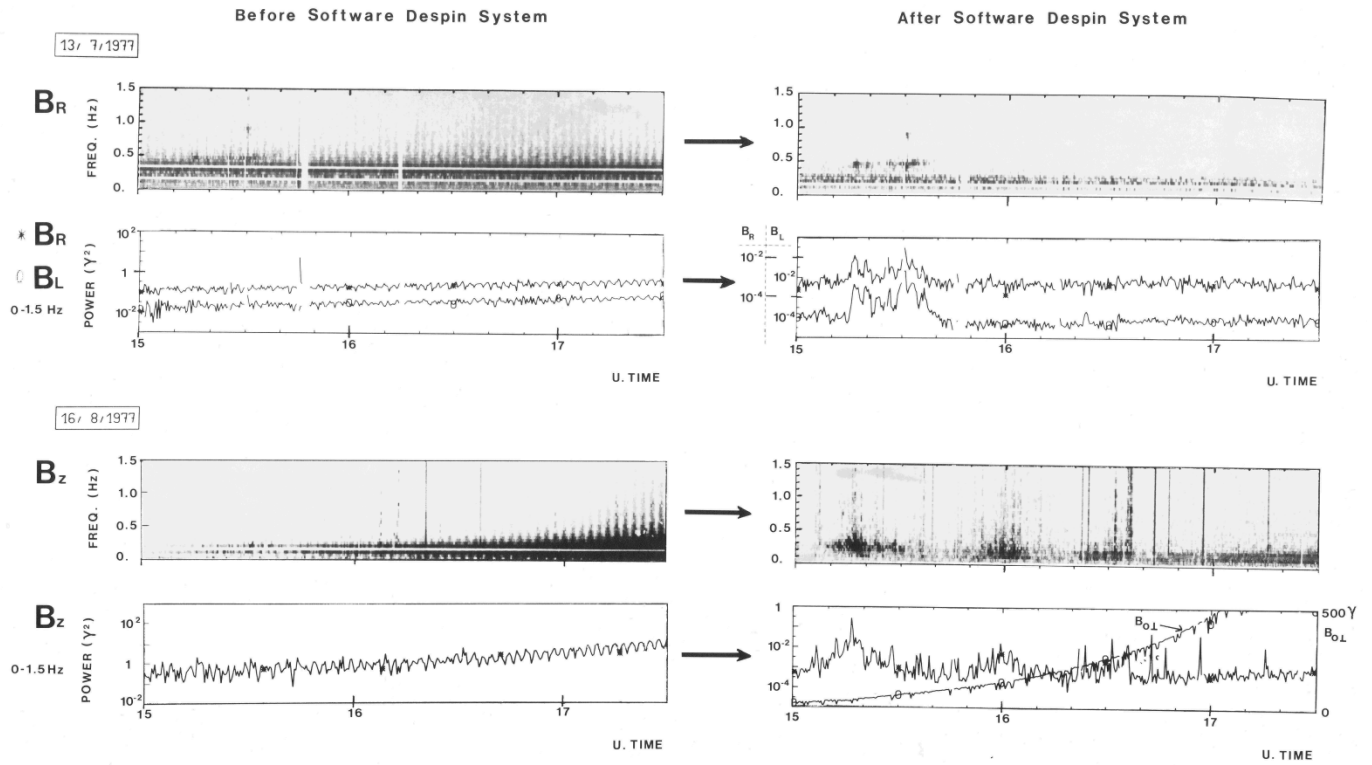


Slide 5. Power spectral density before and after application of software despining system.



Slide 6. Spectrogram and integrated power before and after application of software despin system during a very strong perpendicular DC field until hardware saturation (perigee).

GEOS I: S-300 EXPERIMENTER SUMMARY



Slide 7. Spectrogram and integrated power before and after application of software despin system during normal conditions.